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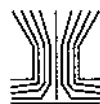
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## Field Study of the Accuracy of Two Respirable Sampling Cyclones

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**ABSTRACT.** This study is to evaluate the sampling bias of a new cyclone (Tsai et al. 1999) and a 10 mm nylon cyclone under field sampling conditions. Both cyclones were operated at the optimum flow rate of 1.7 L/min. The Marple personal cascade impactor was used to measure the particle size distributions, which were used to calculate the reference RPM (Respirable Particulate Matter) concentrations according to the new ACGIH criteria.

A wind tunnel was used in the field to ensure uniform particle concentration and wind speed across the tested cyclones and impactors in the working section. The wind speed, which was varied from 0.8 to 2.3 m/s, was kept constant in the wind tunnel. Near the packaging area of a glazing-making factory (mass median aerodynamic diameter, or MMAD: 11.1  $\mu\text{m}$ ), the average ratio of the RPM concentrations measured by the cyclones to the standard RPM concentrations was found to be 1.20 and 1.10 for the 10 mm nylon and the new cyclone, respectively. Near the packaging area of a lead powder factory (MMAD: 4.82  $\mu\text{m}$ ), the average ratio of the RPM measured by the cyclones to the reference RPM was found to be 1.13 and 1.02 for the 10 mm nylon and the new cyclone, respectively. Wind speed and total airborne particle concentration were found to have little effect on the accuracy of the two respirable cyclones. This field study showed that the new cyclone is more accurate than the 10 mm nylon cyclone based on the reference RPM.

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### INTRODUCTION

The 10 mm nylon cyclone is widely used as a respirable dust sampler in the United States. Most of previous studies on the penetration of the 10 mm nylon cyclone were done under laboratory conditions in

which the particle mass concentration was low and the particle electrostatic charge was neutralized (Ettinger et al. 1970; Seltzer et al. 1971; Caplan et al. 1977a, 1977b; Tsai and Shih 1995). In field sampling conditions, the sampling accuracy of the 10 mm nylon cyclone can be influenced by the particle mass concentration, particle electrostatic charge, wind speed and direction.

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A new cyclone was designed and tested to reduce the effect of deposited particles and particle electrostatic on particle penetration (Tsai et al. 1999). The inner diameter of the new cyclone, 18 mm, is 1.8 times that of the 10 mm nylon cyclone and made of conductive aluminum. Tested at 1.7 L/min in the laboratory, Tsai et al. (1999) found that the particle penetration of the new cyclone matches well with the new ACGIH (1993) criteria for respirable dust sampling and particle electrostatic charge has little effect on particle penetration. Compared to the 10 mm nylon cyclone, variation of cutoff aerodynamic diameter caused by the deposited particles is greatly reduced for the new cyclone.

While the performance of the new cyclone seems to be better than that of the 10 mm nylon cyclone under laboratory conditions, it is important to conduct the test in field conditions. Also, whether or not the operating flow rate for the new cyclone, 1.7 L/min, is the optimum flow rate remains to be determined.

In a study conducted under field conditions, Groves et al. (1994) used the 10 mm nylon, SKC and BGI cyclones to measure the RPM concentrations and compared to those calculated based on the size distributions measured using Marple personal cascade impactors (or standard RPM concentrations) (Rubow et al. 1987). Based on the standard RPM concentrations, the accuracy of the measured RPM concentrations by cyclones were found to be affected by the level of measured cyclone RPM concentrations. The ratio of RPM concentrations measured with cyclones to the standard RPM concentrations increased with cyclone sampled RPM concentrations and was close to unity at 2 mg/m<sup>3</sup>.

In the previous study, airborne particle concentration seemed to be an important factor in this study. (The effect of wind

speed and direction on the measured RPM concentrations was not examined).

In this study, the 8-stage Marple personal impactors were used to measure the size distributions in a glazing-making factory and a lead powder factory. Particles in both factories are solid. The reference RPM concentrations were calculated based on the new ACGIH criteria. The reference RPM concentrations were used as a basis to determine the sampling accuracy of the two cyclones, which were operated simultaneously with the Marple personal impactors in a wind tunnel. In order to investigate the effect of wind speed on the sampling accuracy of the cyclones, aerosol sampling by the cyclones and Marple personal impactors with inlet visor were conducted in the wind tunnel where the wind speed was adjusted from 0.8 to 2.3 m/s. The wind speed is less than the inlet velocity of the two cyclones, which is approximately 6 m/s. The samplers were oriented so that the openings were facing toward the wind.

The cutoff aerodynamic diameter of each stage, the inlet sampling efficiency, the particle rebound problem on coated stage, and particle inner loss for the Marple personal impactor were tested using monodisperse particles in the laboratory (Rubow et al. 1987). The overall sampling effectiveness of the impactor, which was defined as the product of the inlet sampling efficiency and (1.0—the internal particle loss), was determined under calm wind conditions. The effectiveness was shown to be greater than 90% for particles than 7.0  $\mu\text{m}$  in aerodynamic diameter, and was 84% for 10  $\mu\text{m}$  particles in aerodynamic diameter for the impactor, with or without the inlet visor. Although not determined under different wind speeds, it is believed that the sampling effectiveness of the impactor should be similar to that under calm wind

conditions because the inlet visor shields off the wind effectively.

Following the work of Tsai and Cheng (1995), deposit particle mass was considered to be an important factor for the penetration of the Marple personal impactor and was first examined in the laboratory.

The optimum flow rate of the new cyclone was then determined in the laboratory using the method of Bartley and Breuer (1982). The flow rate was then used to operate the new cyclone for determining its sampling accuracy under the field conditions, while the operating flow rate for the 10 mm nylon cyclone was set at 1.7 L/min (Bartley et al. 1994).

### EXPERIMENTAL

The experimental setup used to evaluate the effect of deposited particle mass of the Marple impactor on the particle penetration is shown in Figure 1. When calculating the reference RPM concentrations, such deposited particle mass effect was taken

into account. Monodisperse solid ammonium fluorescein particles and liquid oleic acid particles were generated by a Vibrating Orifice Monodisperse Aerosol Generator (VOMAG, TSI Model 3450, TSI Inc., St. Paul, MN, USA) and passed through a drying and neutralizing column. Each stage of the Marple personal impactor was tested. An Aerodynamic Particle Sizer (APS, TSI Model 3310A) was used to measure the upstream and down stream particle size and concentrations and to determine particle penetration.

The flow rate of Marple impactor was set at 2.0 L/min. The inlet particle concentration ( $N_1$ ) of the Marple impactor was measured before and after experiment to assure the stability of concentration. The outlet particle concentration ( $N_2$ ) was measured and recorded every 20 seconds by the APS continuously. The collection efficiency  $\eta$  of the Marple impactor at any sampling time was calculated as

$$\eta(\%) = \left[ 1 - \frac{N_2}{N_1} \right] \times 100\% . \quad (1)$$

After  $n$  time intervals, particle mass deposited on the stage of the Marple impactor,  $m$ , was calculated as

$$m = \sum_{i=1}^n \left[ \frac{\pi}{6} \rho_p \cdot D_p^3 (N_1 - N_{2,i}) \times Q \times t_i \right], \quad (2)$$

where  $\rho_p$  is the particle density;  $D_p$  is the particle diameter;  $Q$  is the flow rate of the Marple impactor;  $t_i$  is the duration of each sampling interval  $i$ . Monodisperse particles of a certain particle size were used to deposit on the impactor stages to investigate the effect of deposited particle mass on the collection efficiency of that particular size.

In Equation (2), the overall sampling efficiency of solid particles by the APS is assumed to be 100%. Although the overall sampling efficiency is shown to be low for large liquid particles (Kinney and Pui 1995),

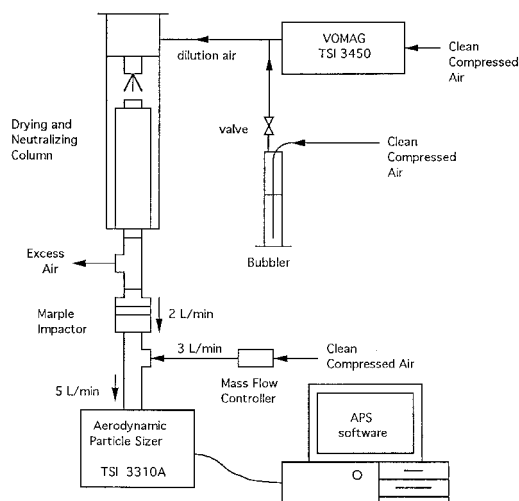


FIGURE 1. Schematic of the experiment setup to obtain the penetration curves for the Marple impactor.

it is considerably higher for solid particles (Blackford et al. 1988). However, there have been no accurate data for overall sampling efficiency of solid particles in the literature. Once the data become available, the particle mass loading can be corrected.

The penetration of a small sampling cyclone was found not only depends on the Stoke number ( $S_{tk}$ ) but also on the deposited particle mass (Tsai et al. 1999). In this study, monodisperse particles of a certain particle size were used to deposit on the impactor stages to investigate the effect of deposited particle mass on the collection efficiency of that particular size.

The  $S_{tk}$  is defined as

$$S_{tk} = \frac{\rho_p D_p^2 C u_i}{18 \mu D}, \quad (3)$$

where  $C$  is the slip correction factor of the particle,  $u_i$  is the inlet velocity of the cyclone,  $\mu$  is the viscosity of air and  $D$  is the inner diameter of the cyclone.

To optimize the flow rate of the new cyclone under different deposited particle mass conditions, particle penetration of the new cyclone at different flow rates and different deposited particle masses must be found. At each flow rate, monodisperse particles of 6.7  $\mu\text{m}$  in aerodynamic diameter were first used to deposit particles of 0, 0.3, 0.6, and 3 mg in the cyclones, then the experimental penetration curves were measured (Tsai et al. 1999). The original experimental data for particle penetration,  $P(\%)$ , at 1.7 L/min for the new cyclone (Tsai et al. 1999) are fitted for four different deposited particle masses: 0, 0.3, 0.6, and 3 mg, based on  $S_{tk}$  as

$$P(\%) = \left( 1 - \frac{1}{1 + \left( \frac{\alpha_1}{\sqrt{S_{tk}}} \right)^{\alpha_2}} \right) \times 100, \quad (4)$$

where the fitting parameter  $\alpha_1 = 0.138, 0.132, 0.127,$  and  $0.126$ ;  $\alpha_2 = 6.19, 5.3, 5.47,$

5.44 for the deposited particle mass of 0, 0.3, 0.6, and 3.0 mg, respectively. Based on the above equation, the particle penetration curve at a flow rate different from 1.7 L/min can be predicted for different deposited particle masses.

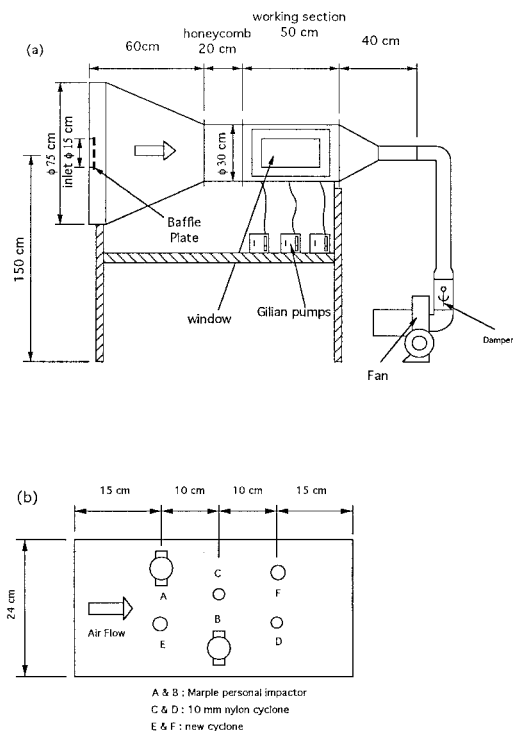
Experimental particle penetration curves of the new cyclone at the flow rate of 1.5, 1.9, and 2.1 L/min were also determined in the laboratory using the experimental setup described in Tsai et al. (1999). After the particle penetration curves at different flow rates are obtained, sampling bias  $\sqrt{\phi(Q)}$  at the flow rate  $Q$  for the new cyclone can be calculated, where  $\phi(Q)$  is expressed as (Bartley and Breuer 1982):

$$\phi(Q) = \int_0^\infty w^2(D_{pa}) \left[ P_c(D_{pa}, Q) - P_R(D_{pa}, Q) \right]^2 dD_{pa}, \quad (5)$$

where  $P_c(D_{pa}, Q)$  and  $P_R(D_{pa}, Q)$  are the penetration of the new cyclone and the new ACGIH criteria, respectively, at the flow rate  $Q$  and particle aerodynamic diameter  $D_{pa}$ . The weighting function  $w(D_{pa})$  is a normalized lognormal distribution function with two parameters, MMAD and GSD. The optimum flow rate is determined as the flow rate at which the sampling bias is the minimum.

The optimum flow rate determined for the new cyclone was then used to operate the new cyclone for determining its accuracy in field sampling, while the flow rate for the 10 mm nylon cyclone was set at 1.7 L/min based on the work of Bartley et al. (1994).

A wind tunnel with the inner diameter of 30 cm in the working section was used to test the sampling accuracy of the 10 mm nylon cyclone and the new cyclone at different wind speeds. The wind tunnel is shown in Figure 2(a). A fan with a flow-control damper drew aerosols in the workplace through a contraction, a baffle plate, a honeycomb, and a working section.



**FIGURE 2. Schematic of the experiment setup for field sampling (a) wind tunnel (b) arrangement of samplers on working platform.**

Two Marple impactors, two 10 mm nylon cyclones, and two new cyclones were collocated in three rows in a platform in the working section as shown in Figure 2(b). The height of the platform was adjusted such that the openings of the samplers were located approximately at the center of the wind tunnel. All openings of the samplers were facing toward the wind. To avoid interference of the samplers, the adjacent rows of the samplers were arranged in a staggered manner.

The uniformity of dust concentration in the working section was measured by gravimetric analysis using 37 mm cassettes installed at the corresponding locations of the samplers. The variation of concentra-

tion was found to be within 5% at different wind speeds. Each sampler was driven by a Gilian pump. PE filters coated with silicon oil were used as substrates for the Marple impactor. The after filter of the Marple impactor was a PVC filter, which was also used for the filter cassettes of the 10 mm nylon cyclones and the new cyclones.

A glazing-making and a lead powder factory were chosen for the field test. During the test, temperature and humidity ranged from  $19 \pm 5^\circ\text{C}$  and  $76 \pm 8\%$ , respectively. The tests were conducted near the packaging areas of both factories. Each sampling continued for 4–5 hours to collect enough particles for weighing. At each sampling location, four runs were conducted for each wind speed, which was kept constant at 0.8, 1.3, 1.8, or 2.3 m/s in the working section during the test runs. In total, there were 16 runs at each sampling location.

The reference RPM concentration was calculated from the particle size distribution measured by the Marple impactor applying the new ACGIH criteria for respirable sampling. Size distribution data were first corrected for the deposited particle mass effect determined in this study, and the inlet efficiency and inter-stage particle loss according to the data reported in Rubow et al. (1987). The TSI DISFIT program was then used to fit the data in order to calculate the reference RPM concentrations. The RPM concentrations measured by the 10 mm nylon cyclone and the new cyclone were then compared with the reference RPM concentrations.

## RESULTS AND DISCUSSIONS

### *Effect of Deposited Particle Mass on Particle Penetration for the Marple Impactor*

The penetration efficiency data obtained in this study were found to be slightly different from those of Rubow et al. (1987) for

**TABLE 1. Comparison of cutoff aerodynamic diameter\* ( $\mu\text{m}$ ) at different deposited particle masses for the Marple Personal Impactor**

Particles	Deposited mass (mg)	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Remarks
Liquid	—	21.3*	14.8	9.8	6.0	3.5	1.55	0.98	0.52	Rubow et al. (1987)
Liquid	—	19.65	13.6	9.67	6.1	3.3	—	—	—	This study
Solid	0	18.8	13.3	9.9	5.9	3.4	—	—	—	This study
	0.01	—	—	—	—	3.8	—	—	—	
	0.05	—	13.3	10.0	6.14	3.95	—	—	—	
	0.5	19.6	14.1	10.4	6.4	—	—	—	—	
	1.0	20.0	14.4	10.5	—	—	—	—	—	

stage 1–5 of the Marple impactor. In this study, the cutoff aerodynamic diameter was found to be 19.65, 13.6, 9.67, 6.1, and 3.37  $\mu\text{m}$  for the stage 1–5, respectively. Compared to the cutoff aerodynamic diameters reported in Rubow et al. (1987), the difference is  $-7.7\%$ ,  $-8.1\%$ ,  $-1.3\%$ ,  $+1.7\%$ , and  $-3.7\%$  for stage 1–5, respectively, as shown in Table 1. For liquid particles, the amount of deposited particle mass was found to have no effects on the particle penetration of the Marple impactor.

For solid particles, the penetration curves of different deposited particle masses were obtained in this study. It was found that as deposited particle mass increased, the particle penetration decreased. For example, for Stage 1 the cutoff aerodynamic diameter is 18.8, 19.6, and 20.2  $\mu\text{m}$  when the deposited particle mass is 0 mg (clean impaction surface), 0.5 mg and 1 mg, respectively. For Stage 2, the cutoff aerodynamic diameter is 13.3, 13.3, 14.1, and 14.4  $\mu\text{m}$  when the deposited particle mass is 0 mg, 0.05 mg, 0.5 mg, and 1 mg, respectively. The shift in penetration curves and cutoff aerodynamic diameter with deposited particle mass was taken into account when calculating the reference RPM concentrations based on the measured size distributions by the Marple impactors.

### *Optimization of the Flow Rate for the New Cyclone*

The predicted and experimental penetration curves in the new cyclone at different flow rates were obtained for different deposited particle masses. Only the cases for the deposited mass of 0 and 3 mg are shown in Figure 3(a) and (b), respectively. The figures indicate that the agreement between the theoretical predictions and experimental data is quite satisfactory. When the deposited particle mass is 0 mg, that is the inner wall of the cyclone is clean, the theoretical cutoff aerodynamic diameters are 4.54, 4.29, 4.04, and 3.84  $\mu\text{m}$  at the flow rate of 1.5, 1.7, 1.9, and 2.1 L/min, respectively. These cutoff diameters are very close to the experimental data of 4.67, 4.29, 4.16, and 3.74  $\mu\text{m}$  at the flow rate of 1.5, 1.7, 1.9, and 2.1 L/min, respectively. Difference between the theoretical predictions and experimental data is less than 3.0% for all the flow rates.

Similarly, when the deposited mass is 3 mg for the new cyclone, the theoretical cutoff aerodynamic diameters are 4.15, 3.89, 3.68, 3.50  $\mu\text{m}$  for the flow rate of 1.5, 1.7, 1.9, and 2.1 L/min, respectively, which also are very close to the experimental data of 4.28, 3.91, 3.66, and 3.44  $\mu\text{m}$  at the corre-



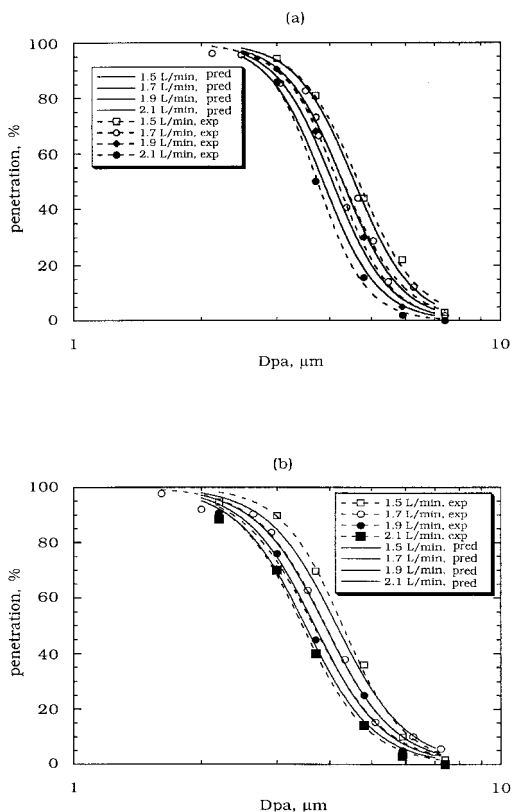


FIGURE 3. Predicted and experimental particle penetration curves at different flow rates for the new cyclone. (a) Deposited mass: 0 mg (b) Deposited mass: 3 mg. Solid curves = predicted; dotted curves = best fitted through experimental data.

sponding flow rate. Other cases for different deposited masses show similar good agreement between the theoretical predictions and experimental data. That is, when the penetration efficiency curve is determined for a cyclone at a flow rate, the penetration curve for a different flow rate can be predicted accurately if the deposited particle mass remains the same.

Assuming that the dust is log-normal and GSD = 2.5 and MMAD = 2, 4, 6, 8, 10, 12 μm,  $\phi$  for the cyclones is calculated for deposited particle masses. Figures 4(a) and

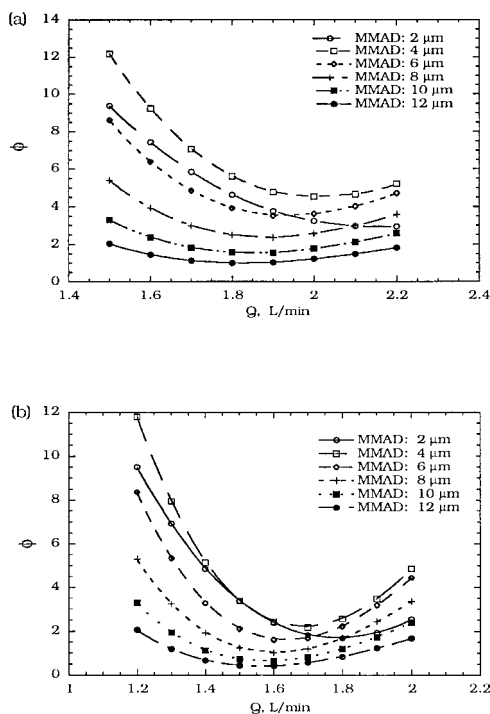


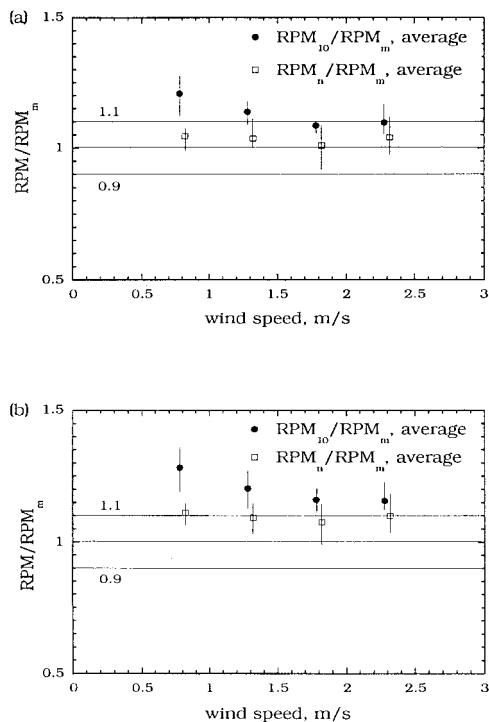
FIGURE 4.  $\phi$  at GSD = 2.5 and different MMADs at different flow rates for the new cyclone. (a) Deposited mass: 0 mg (b) Deposited mass: 3 mg.

(b) show the case for deposited particle mass of 0 and 3 mg, respectively. Depending on MMAD, it can be seen that the optimal flow rate (when  $\phi$  is minimum) ranges from 1.82 to 2.04 L/min when the deposited mass is 0 mg, or from 1.50 to 1.82 L/min when the deposited mass is 3 mg. For the deposited particle mass of 0.3 and 0.6 mg, the corresponding optimum flow rate for the new cyclone has also been determined to be 1.75 to 1.93 L/min and 1.64 to 1.72 L/min, respectively. As the deposited particle mass in the cyclone is usually on the order of several tenths of a milligram for a typical 8-hour sampling in the workplace, set the optimum flow rate to be 1.7 L/min is seen to be good choice for the new cyclone.

### Field Comparison of RPM Concentrations

In the glazing-making factory, the experimental data showed that the average MMAD was  $11.1 \mu\text{m}$  and GSD was 2.73 for the aerosols. The total airborne particle concentration, as determined from the sum of the concentrations of each stage and after filter of the Marple impactor, ranged from 1.65 to  $4.4 \text{ mg}/\text{m}^3$ . The RPM concentrations averaged about 23% of the total airborne particle concentrations. At the wind speed of 0.8, 1.3, 1.8, and 2.3 m/s, the average ratio of the RPM concentration measured by the cyclones, denoted as  $\text{RPM}_n$  (new cyclone) or  $\text{RPM}_{10}$  (10 mm nylon cyclone), to the reference RPM concentration (denoted as  $\text{RPM}_m$ ) is shown in Figure 5(a). The range of each data point is also indicated in the figure. The calculation of  $\text{RPM}_m$  is based on the size distribution corrected for the inter-stage loss and inlet efficiency for the Marple impactor, but the deposited particle mass effect on particle penetration is not corrected. When the  $\text{RPM}_m$  is corrected for deposited particle mass, the corresponding experimental data are shown in Figure 5(b).

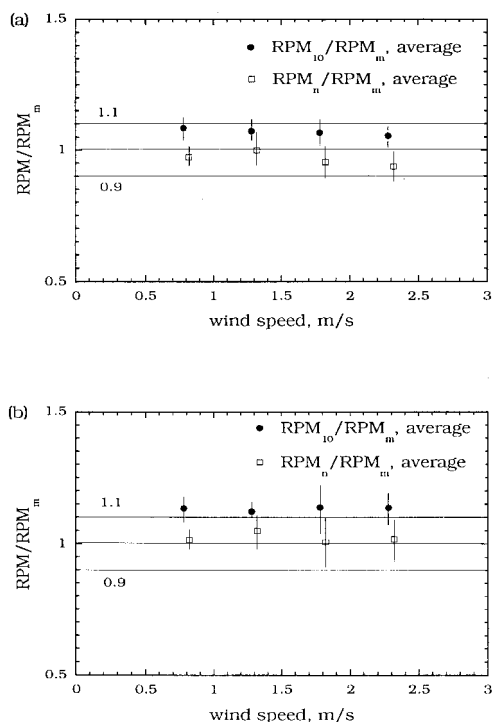
It is seen from Figures 5(a) and (b) that RPM concentrations measured by both cyclones are higher than the reference RPM concentrations. The RPM concentration measured by the new cyclones are closer to the reference RPM concentration than those measured by the 10 mm nylon cyclones. Considering all wind speeds, the  $\text{RPM}_{10}/\text{RPM}_m$  ratio averages  $1.13 \pm 0.13$  (average  $\pm 2$  standard deviation) for the 10 mm nylon cyclone, and the  $\text{RPM}_n/\text{RPM}_m$  ratio averages  $1.03 \pm 0.10$  for the new cyclone, as shown in Figure 5(a). While the wind speed has some effect on the ratio  $\text{RPM}_{10}/\text{RPM}_m$ , the effect is not obvious for the  $\text{RPM}_n/\text{RPM}_m$  ratio. As the deposited mass effect on particle penetration is corrected for  $\text{RPM}_m$ , the ratio becomes



**FIGURE 5.** Ratio of RPM concentrations determined by cyclones to reference RPM concentrations ( $\text{RPM}_m$ ), glazing-making factory (a) without correction for deposited particle mass (b) with correction for deposited particle mass.  $\text{RPM}_{10}$  = 10 mm nylon cyclone;  $\text{RPM}_n$  = new cyclone.

7% higher for both  $\text{RPM}_n/\text{RPM}_m$  and  $\text{RPM}_{10}/\text{RPM}_m$ , as shown in Figure 5(b).

Particles in the lead powder factory were smaller than those in the glazing-making factory. The average MMAD was  $4.82 \mu\text{m}$  and GSD was 2.26 for the dust particles for all the test runs. The total airborne particle concentration ranged from 0.16 to  $0.43 \text{ mg}/\text{m}^3$  and the RPM concentration averaged about 46% of the total airborne particle concentrations. The  $\text{RPM}/\text{RPM}_m$  ratio is shown in Figure 6(a) ( $\text{RPM}_m$  is not corrected for deposited particle mass) and Figure 6(b) ( $\text{RPM}_m$  is corrected for deposited particle mass). It is seen that both cyclones sampled RPM concentrations at this fac-



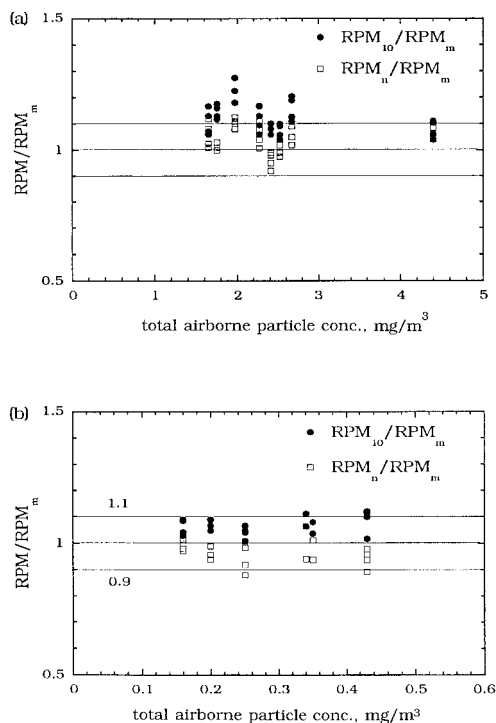
**FIGURE 6.** Ratio of RPM concentrations determined by cyclones to reference RPM concentrations ( $RPM_m$ ), lead powder factory (a) without correction for deposited particle mass (b) with correction for deposited particle mass.  $RPM_{10}$  = 10 mm nylon cyclone;  $RPM_n$  = new cyclone.

tory more accurately than at the previous factory. The  $RPM_{10}/RPM_m$  ratio averages  $1.07 \pm 0.07$  for the 10 mm nylon cyclone, and the  $RPM_n/RPM_m$  ratio averages  $0.97 \pm 0.095$  for the new cyclone for all wind speeds, as shown in Figure 6(a). When the  $RPM_m$  is corrected for deposited particle mass, the  $RPM_{10}/RPM_m$  ratio becomes  $1.13 \pm 0.07$  and the  $RPM_n/RPM_m$  ratio becomes  $1.02 \pm 0.095$ , as shown in Figure 6(b). In all cases, the new cyclones again appear to sample RPM more accurately than the 10 mm nylon cyclones. And the wind speed does not seem to influence the  $RPM/RPM_m$  ratio for any of the cyclones.

The effect of the total airborne particle concentrations on the  $RPM/RPM_m$  ratios is shown in Figures 7(a) and (b) for the glazing-making factory and lead powder factory, respectively. The figures show that the total airborne particle concentrations do not seem to influence the sampling accuracy of neither cyclone in the range of total airborne particle concentrations measured in this study.

## CONCLUSIONS

In the field study in both glazing-making and lead powder factories, RPM concentrations measured by the new cyclone were



**FIGURE 7.** Ratio of RPM concentrations determined by cyclones to reference RPM concentrations ( $RPM_m$ ), without correction for deposited particle mass, different total airborne particle concentrations. (a) glazing-making factory (b) lead powder factory.  $RPM_{10}$  = 10 mm nylon cyclone;  $RPM_n$  = new cyclone.

found to be closer to the reference RPM concentrations than those measured by the 10 mm nylon cyclones. In the glazing-making factory where the solid particles were large with MMAD averaged about 11  $\mu\text{m}$ , errors in the measured RPM by the cyclones were found to be larger. The new cyclones over-sampled the RPM concentration by less than 10% while the 10 mm nylon cyclone over-sampled by less than 20%.

When sampling smaller particles such as in the lead powder factory with MMAD averaged about 4.8  $\mu\text{m}$ , the RPM concentrations measured by both cyclones were closer to the reference RPM concentrations. Again the 10 mm nylon cyclone over-sampled by less than 10% while the new cyclone was shown to sample RPM concentrations accurately within experimental errors.

Results of this field study also indicated that the effect of the total airborne particle concentrations on the measured RPM concentrations of the cyclones is negligible. The effect of wind speed ranging from 0.8 to 2.3 m/s on the measured RPM concentrations of the cyclones is also negligible, except for the 10 mm nylon cyclones sampling at the glazing-making factory.

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